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(54) Abstract Title
Detecting the position of a mechanical interaction

(57) The position of a mechanical interaction is determined using a detector constructed from fabric. A substantially constant electric current is established through the elements of the detector. A first electrical potential developed in a first plane is measured in response to the said constant current. The second electrical potential developed in a second plane is also measured in response to said current. These measurements are processed to identify a position of the mechanical interaction.

The apparatus may be constructed from a fabric material incorporating two conductive layers.

A calibration means comprised an alternative route, for the constant current, which is not used during measurement.

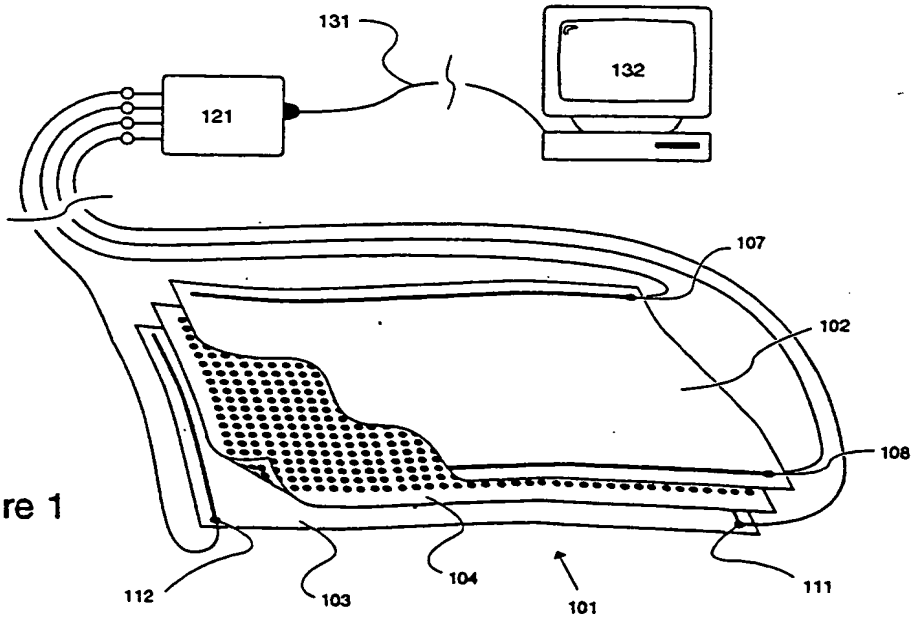

Figure 1

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Detecting the Position of a Mechanical Interaction

The present invention relates to a detector constructed from fabric having electrically conductive elements to define at least two electrically conductive planes.

A fabric touch sensor for providing positional information is described in United States patent 4,659,873 of Gibson. The sensor is fabricated using at least one resistive fabric layer in the form of conducting threads. This fabric is constructed using either uni-directional threads or crossed threads formed by overlaying one set with another or weaving the two sets together. The fabric is separated from a second resistive layer to prevent unintentional contact by separators in the form of non-conducting threads, insulator dots or with an air gap. Both resistive layers are fabrics formed from conductive threads such that no pre-forming is required in order to adapt the sensor to a contoured object.

A problem with the sensor described in the aforesaid United States patent is that it is only capable of identifying the location of the mechanical interaction and cannot provide additional information about the interaction.

A touch sensor for providing positional information is described in United States patent 4,487,885 of Talmage, which also provides a signal dependent upon the pressure or force applied. However, the sensor described is made from a printed circuit board and a flexible sheet of rubber, elastomer or plastic and as such it does not have the many physical qualities that a fabric may provide.

An improvement to this proposal is disclosed in the applicant's co-pending British patent application number 98 20 902.6 in which there is 2040-P101-GB provided a position detector constructed from fabric having electrically

conductive elements, comprising at least two electrically conductive planes. A potential is applied across at least one of the planes to determine the position of a mechanical interaction. In addition, a second electrical property is determined, such as current, to identify additional properties of the mechanical interaction, such as an applied force, an applied pressure or an area of contact.

The position detector, constructed from fabric, facilitates bending and folding operations. However, a problem with the disclosed construction is that the electrical characteristics of the detector are unreliable if the detector planes are folded or distorted beyond modest operational conditions. Certain folding or bending of the sensor can cause pressures within the fabric similar in magnitude to those pressures desired to be measured, leading to undesirable output response characteristics.

A further limitation of the aforementioned disclosures, is that switching arrangements employed to perform position detection may result in undesirable radio frequency emissions. In the particular case of a fabric position detector, it may be desirable to have the fabric in close proximity to an operator, possibly being worn as an article of clothing. Under these circumstances, radio frequency emissions must be kept to a level that may not be achievable using the disclosed detector arrangements.

According to an aspect of the present invention, there is provided a method of detecting the position of a mechanical interaction in a sensor constructed from fabric, wherein a substantially constant electric current is established through said elements, including steps of measuring a first electrical potential developed in a first plane in response to said current; measuring a second electrical potential developed in a second plane in response to said current; and processing said measurements to identify a

position of said mechanical interaction.

The present invention will now be described by way of example only, with reference to the accompanying drawings, of which:

Figure 1 shows a position detector constructed from fabric, including outer planes, a central layer and a control circuit;

Figure 2 shows the control circuit identified in *Figure 1*;

Figure 3 details operations performed by the micro-controller identified in *Figure 2*;

Figure 4 details construction of the outer planes and central layer shown in *Figure 1*;

Figure 5A details current flow in the sensor shown in *Figure 4*, in a first mode of measurement;

Figure 5B details current flow in the sensor shown in *Figure 4*, in a second mode of measurement;

Figure 6 details a schematic representation of current flowing in the sensor arrangement shown in *Figure 1*, in response to signals issued by the circuit shown in *Figure 2*;

Figure 7 details a cross sectional view of the type of sensor shown in *Figure 4* under conditions of folding, creasing and deliberate applied force;

Figure 8 details a cross sectional view of an alternative sensor construction under conditions of folding, creasing and deliberate applied force;

Figure 9 illustrates physical and electrical characteristics of the sensor shown in *Figure 7*;

Figure 10 illustrates physical and electrical characteristics of the sensor shown in *Figure 8*;

Figure 11 illustrates physical and electrical characteristics of a

composite sensor comprising the sensors shown in *Figures 7* and *8*;

Figure 12 details a cross sectional view of an further alternative sensor construction under conditions of folding, creasing and deliberate applied force;

Figure 13 details a cross sectional view of a further alternative sensor construction under conditions of folding, creasing but without deliberate applied force; and

Figure 14 shows an improved control circuit of the type shown in *Figure 1*.

The invention will now be described by way of example only with reference to the previously identified drawings.

A position detector **101** constructed from fabric is shown in *Figure 1*. The detector has two electrically conducting fabric planes, in the form of a first plane **102** and a second plane **103**. The planes are separated from each other by means of a partially conductive central layer **104**. Partial conduction may be achieved in accordance with one or several of a plurality of arrangements, to be described later.

When force is applied to an area of the sensor, the two outer conducting planes **102** and **103** are brought into contact with central layer **104**. The central layer is partially conductive, and, therefore, electrical current may flow between planes **102** and **103** in the region where the force has been applied. It is then possible to identify properties relating to a mechanical interaction.

The planes **102**, **103** and preferably the central layer **104** are constructed from fabric, which may be woven, non-woven (felted), knitted or a composite structure. The fabric layers may be manufactured separately and then combined to form the detector or the whole structure may be

created as part of the textile manufacture process.

When a voltage is applied across terminals **107** and **108**, a voltage gradient appears across plane **102**. When a mechanical interaction takes place, plane **103** is brought into electrical contact with plane **102** via the central layer **104**, and the actual voltage applied to plane **103** will depend upon the y axis position of the interaction. In drawing in *Figure 1*, the y axis is approximately vertical, with the x axis horizontal. Similarly, when a voltage is applied between connectors **111** and **112**, a voltage gradient will appear across plane **103** and mechanical interaction will result in a voltage being applied to plane **102**. The voltage applied to plane **102** will depend upon the x axis position of the interaction. In this way, for an area of mechanical interaction, it is possible to identify a location within the plane with reference to the two aforesaid voltage measurements. If the electrical resistance between terminals **111** and **108** is measured, a reading relating to the applied pressure is obtained. Variations in this reading due to variations in x and y position may be reduced by also measuring the electrical resistance between terminals **107** and **112**. Thus, connectors **107**, **108**, **111** and **112** are connected to a control circuit **121**, configured to apply signals to the detector **101** and to make measurements of electrical properties that vary in response to mechanical interactions.

Control circuit **121** identifies electrical characteristics of the sensor **101** and in response to these identifications, data relating to the characteristics of the sensor environment are supplied to a data processing system, such as a computer **132**, via a conventional serial interface **131**.

The control circuit **121** is detailed in *Figure 2*. The control circuit includes a micro-controller **201** such as a Philips 80C51 running at a clock frequency of twenty megahertz. Operations performed by micro-controller

201 are performed in response to internally stored commands held in an internal two kilobyte read-only memory. The micro-controller also includes one hundred and twenty-eight bytes of static RAM to facilitate intermediate storage while performing calculations and serial communications. The micro-controller **201** includes a serial interface **202** and an interface for communicating with an analogue to digital converter **203**, arranged to convert input voltages into digital signals processable by the micro-controller **201**. Seven pins from port 0 on the micro-controller are designated as outputs C0 to C6, and these are used to control the sensor interface circuitry.

The control circuit **121** includes two PNP transistors **211** and **212**, in addition to four NPN transistors **213**, **214**, **215** and **216**. All of the transistors are of relatively general purpose construction and control switching operations within the control circuit so as to control the application of voltages to the position detector **101**.

In operation, a first measurement is made while a voltage is applied across the first plane **102**. An additional measurement is made while a voltage is applied across the second plane **103**. A voltage output only being applied to one of the planes at any particular time. When an output voltage is applied to one of the planes, plane **102** or plane **103**, input signals are received from the opposite plane **103** or **102** respectively. Input signals are received by the analogue to digital converter **203** via a selection switch **221**, implemented by a CMOS switch, in response to a control signal received from pin C6 of the micro-controller **201**. Thus, in its orientation shown in *Figure 2*, switch **221** has been placed in a condition to receive an output from a first high impedance buffer **222**, buffering an input signal received from plane **102**. Similarly, when switch **221** is placed in its alternative condition, an input is received from a second high impedance buffer **223**, configured to

receive an input signal from plane **103**. By placing buffers **222** and **223** on the input side of CMOS switch **221**, the switch is isolated from high voltage electrostatic discharges which may be generated in many conditions when the detector undergoes mechanical interactions.

In the condition shown in *Figure 2*, switch **221** is placed in its upper condition, receiving input signals from buffer **222**, with output signals being supplied to the second plane **103**. Further operation will be described with respect to this mode of operation and it should be appreciated that the roles of the transistor circuitry are reversed when switch **221** is placed in its alternative condition. As previously stated, condition selection is determined by an output signal from pin C6 of micro-controller **201**. In its present condition the output from pin C6 is low and switch **221** is placed in its alternate configuration when the output from pin 6 is high.

Output pin C0 controls the conductivity of transistor **211** with pins C1 to C5 having similar conductivity control upon transistors **212**, **213**, **214**, **215** and **216** respectively.

Transistors **211** and **213** are switched on while a voltage is applied to the first plane **102**. They are switched off while a voltage is applied to the second plane **103**. Similarly, while a voltage is applied to the second plane **103**, transistors **212** and **215** are switched on with transistors **211** and **213** switched off. In the configuration shown in *Figure 2*, with switch **221** receiving an input from buffer **222**, output transistors **211** and **213** are switched off, and output transistors **212** and **215** switched on. This is achieved by output pin C0 being placed in a high condition and pin C1 being placed in a low condition. Similarly, pin C3 is placed in a low condition and pin C4 is placed in a high condition.

In the configuration shown, C3 is placed in a low condition, as

previously described. The micro-controller **201** includes a pull-down transistor arranged to sink current from the base of transistor **212**, resulting in transistor **212** being switched to saturation conduction. Consequently, transistor **212** appears as having a very low resistance, thereby placing terminal **111** at the supply voltage of five volts. Resistor **231** (4K7) limits the flow of current out of the micro-controller **201**, thereby preventing thermal destruction of the micro-controller's internal output transistor.

Pin C4 is placed in a high state, resulting in transistor **215** being placed in a conducting condition. A serial resistor is not required given that the micro-controller **201** includes internal pull-up resistors, as distinct from a pull-up transistor, such that current flow is automatically restricted. Thus, transistors **212** and **215** are both rendered conductive by driving them into saturation, resulting in terminal **111** being placed substantially at the positive supply rail voltage and terminal **112** being placed substantially at ground voltage. The capacitors shown in the circuit, such as capacitor **219**, limit the rate of transistor switching transitions, thereby reducing radio frequency emissions from the sensor **101**.

When transistors **212** and **215** are placed in their conductive condition, input signals are received from the first plane **102** in the form of a voltage at terminal **108**. For position detection, this voltage is measured directly and transistor **214** is placed in a non-conductive condition by output pin C2 being placed in a low condition. Under these conditions, the voltage from input terminal **108** is applied to analogue to digital converter **203** via buffer **222** and switch **221**.

The current flowing through the sensor in response to a mechanical interaction is then determined. The current measurement is made by placing transistor **214** in a conductive condition by placing output pin C2 in a high

condition, and by placing output pin C4 in a low condition, hence switching transistor **215**. In this condition, current received at terminal 108 is supplied to transistor **214** via resistor **214A**, having a resistance of typically 5k, but selectable so as to correspond to the resistance characteristics of the sensor. A voltage is supplied to the A to D converter **203** via buffer **222** and switch **221**. On this occasion, however, the voltage represents a voltage drop across resistor **214A**.

Thus, transistors **212** and **215** are placed in a conducting condition, transistor **214** is placed in a non-conducting condition, so as to measure voltage, and is then placed in a conducting condition, with **215** in a non-conducting condition, so as to measure current. The roles of the transistors are then reversed, such that output transistors **211** and **213** are placed in a conducting condition, with transistors **212** and **215** being placed in a non-conducting condition, and switch **221** reversed, allowing a voltage to be measured by placing transistor **216** in a non-conducting condition, and then allowing a current to be measured by placing transistor **213** in a non conducting condition, and transistor **216** in a conducting condition.

The cycling of line conditions, in order to make the measurements identified previously, is controlled by a timer circuit within micro-controller **201**. After each condition has been set up, a twelve bit number is received from the digital to analogue converter **203** and this number is retained within a respective register within the micro-controller **201**. Thus, after completing a cycle of four measurements, four twelve bit values are stored within the micro-controller **201** for interrogation by the processing device **131**. Furthermore, the rate of cycling may be controlled in response to instructions received from the computer **132**.

Operations performed by the micro-controller **201** are detailed in

Figure 3. The micro-controller continually cycles between its four configuration states and each time a new input is produced, representing a current or a voltage in one of the two configurations, new output data is calculated on an on-going basis. Thus, output registers are updated such that the best data is made available whenever the micro-controller is interrupted by the external processor **131**.

The micro-controller **201** is fully interrupt driven. It can respond to interrupts for data interrogation, generated in response to receiving a serial data signal from the computer **132**, and several other interrupt sources generated internally.

Internally, interrupts for the micro-controller **201** are generated by its own internal timer and the procedure shown in *Figure 3* is effectively held in a wait state until a next timer interrupt is received at step **301**. The wait state allows voltage levels on connections **107**, **108**, **111** and **112** to become stable and provides sufficient time for valid data to be received from the analogue to digital converter **203**.

At step **302**, an output is received from the analogue to digital converter **203** and at step **303** calculations are performed with respect to the most current data received from the analogue to digital converter, so as to convert numerical values relating to voltages and currents into numerical values representing properties of the mechanical interaction. Thus, after performing calculations at step **303**, appropriate registers are updated at step **304** and it is these registers that are usually interrogated in response to an interrupt received from processing system **131**.

At step **305** the next conditions for the output lines are set by appropriate logic levels being established for output pins C0 to C6. After the next output condition has been selected, the processor enters a wait state at

step **306**, allowing the electrical conditions of the interface and the sensor circuitry to settle, whereafter processing continues in response to the next timer interrupt.

Thus, it should be appreciated that on each iteration of the procedure shown in *Figure 3*, one of the output conditions is selected at step **305**. The input data generated at step **302** is a measurement made in response to conditions of C0 to C6 that were set up during the previous cycle. The delay is made large enough to ensure that electrical characteristics have time to settle, and that A to D conversion may take place.

When output condition number one is selected, an output voltage at **108** is determined. On the next cycle, identified as output condition number two, the current flowing through connector **108** is determined. On the next iteration, under output configuration number three, the voltage appearing at connector **112** is determined and on the next cycle, identified as condition number four, the current flowing through connector **112** is determined. After each of these individual measurements, new data is generated in response to steps **303** and **304** such that resulting output registers are being regularly updated on a continual basis, such that the processing system **131** may effectively perform a continual monitoring operation in terms of changes made to the mechanical interactions with the detector **101**.

In a typical implementation, the four characteristic measurements, making up a complete cycle, will be repeated at a frequency of between twenty-five to fifty times per second. In situations where such a repetition rate is not required, it may be preferable to increase the duration of the wait states and thereby significantly reduce overall power consumption. In some instances, when a measurement is made only a few times per second, it is possible to enter the micro-controller into a power-down mode, thereby

reducing power dissipation and reducing consumption in a battery-operated environment. Alternatively, power consumption may be reduced by triggering an interrupt when a current flows across the fabric detector. This requires additional circuitry, not shown in *Figure 2*.

Planes **102**, **103** and **104** of the detector 101 are detailed in *Figure 4*. Planes **102** and **103** are of substantially similar construction and are constructed from fabric having electrically conductive elements **401** and **402** in plane **103** along with similar electrical conductive elements **403** and **404** in plane **102**. Relatively low resistance conductive elements **112** and **111** are incorporated in plane **103**, and relatively low resistance conductive elements **107** and **108** are incorporated in plane **102**. Thus, it is possible for a voltage indicative of position to be determined when conductive elements **402** are placed in electrical contact with conductive elements **404**, via the central layer **104**.

Horizontal and vertical directions are referred to as warp and weft in the context of woven fabrics. The overall resistivity in each of warp and weft directions of planes **102** and **103** are controlled by the inclusion of non-conducting elements **405**. Thus, resistivity is controlled by setting the relative quantities and/or densities of conductive elements **401**, **402**, **403** and **404**, with non conductive elements **405**. Resistivity may also be controlled by selecting an appropriate fibre type, adjusting the thickness of the fibre or adjusting the number of strands present in a yarn.

A suitable fibre for conductive elements **401**, **402**, **403** and **404** is "Resistat" ® type F901, 22 denier carbon impregnated nylon 6, available from BASF and commonly used in static electricity dissipation applications. A suitable fibre for relatively low resistance conductive elements **107**, **108**, **111** and **112** is "Aracon" ® type XNO400E-018 shielding grade nickel coated

aramid fibre, available from DuPont and commonly used in electromagnetic shielding applications.

The low resistance conductive elements may be attached to, or incorporated into the fabric construction as part of the weaving process. Alternatively, they may be formed of a suitable conductive material, and achieved by printing, or by selective electroplating.

Central layer **104** is constructed from fabric or other deformable material having recessed electrically conductive elements **411** continuing through the thickness of the plane **104**, together with a raised non conductive element **412**. Conductive elements **411** are electrically isolated from each other in the x and y directions by the non-conductive element **412**. The non-conductive element **412** may be formed from fabric having open spaces corresponding to conductive elements **411** with printed conductive material such as elastomeric conductive polymer forming conductive elements **411**. The conductive material may be selected so as to have variable resistance according to applied pressure, or may be of a relatively incompressible material, therefore having a more stable resistivity.

As an alternative to recessing the conductive elements **411** in central layer **104**, conductive elements **401**, **402**, **403** and **404** may be formed within planes **102** and **103**, using fibre or yarn with a smaller diameter than the non-conducting elements **405**. In this way, using certain configurations of fabric structure, conductive elements **401**, **402**, **403** and **404** are recessed below the surface contour of planes **102** and **103**. Non-conducting elements **405** may also incorporate a readily deformable material such as neoprene fibres to facilitate a linear response to applied pressure.

When a potential is applied across one of the conducting planes, the actual potential detected at a point on that plane will be related to the position

at which the measurement is made. Thus, a direct voltage measurement from the co-operating plane gives a value from which a positional co-ordinate may be determined. By reversing the plurality of the planes and taking a measurement from the opposing plane, two co-ordinates are obtained from which it is then possible to identify a precise location over the planar surface.

As previously described, the system is configured to measure currents in addition to measuring voltages.

When the two conducting planes are brought into electrical contact, due to a mechanical interaction, the amount of current flowing as a result of this contact will vary in dependence upon the actual position in the plane where the mechanical interaction takes place.

Figure 5A illustrates the current flow within detector **101** at step #2 of the measurement cycle shown at **305** in *Figure 3*. The amount of current flowing due to a mechanical interaction will depend upon the position of a mechanical interaction **521**. However, in addition to this, the amount of current flow will also depend upon the size of the mechanical interaction. As the size of the mechanical interaction increases, there is a greater area of contact and as such the overall resistance of the mechanical interaction is reduced. However, it should be appreciated that variations in terms of current with respect to interaction size is a sophisticated relationship, given that, in addition to the resistivity of the contact area **521**, the resistivity of the actual electrical connections within the sheet must also be taken into account.

Thus, current supplied to the low resistance element **111** is transmitted across plane **103** through a region **511** in order to provide a current to the contact region **521**. Similarly, current is transmitted across plane **102** from the contact region **521** to low resistance element **108**. Thus, the total electrical resistance between **111** and **108** is composed of the sum

of the resistance of regions **511**, **512** and the contact region **521**, with the resistance of **511** and **512** being variable, according to the position of the mechanical interaction. The resistance of contact region **521** is variable according to area of contact and the applied force.

Similarly, *Figure 5B* illustrates the current flow within detector **101** at step #2 of the measurement cycle shown at **305** in *Figure 3*.

Current supplied to the low resistance element **107** is transmitted across plane **102** through a region **513** in order to provide a current through the contact region **521**. Similarly, current is transmitted across plane **103** from the contact region **521** to low resistance element **112**. The total electrical resistance between **107** and **112** is composed of the sum of the resistance of regions **513**, **514** and the contact region **521**, with the resistance of **513** and **514** being variable, according to the position of the mechanical interaction.

For a given area of mechanical interaction the resistance of **511** plus the resistance of **514** will be approximately constant, regardless of the x position of the mechanical interaction. The value of the constant is related to the sheet resistance of the planes **102** and **103**, and to the area of the mechanical interaction. Similarly, for a given area of mechanical interaction, the resistance of **512** plus the resistance of **513** will be approximately constant, regardless of the y position of the mechanical interaction. Thus, by using two measurements as previously described, a reading approximately proportional to the resistance of the contact region **521** can be derived which will not vary significantly in relation to variations in x and y position of the mechanical interaction.

A further advantageous characteristic is obtained for a position sensor, when the resistivity of the outer planes **102** and **103** is anisotropic, that is to say, dependent upon the direction of current flow. For greatest accuracy

current is able to flow easily in the direction perpendicular to the voltage gradient, but less easily in the direction of the voltage gradient. Again, this reduces the paths for current flow which interfere with the process of pressure and area measurement, that are derived from measurements of current flow. However, since conductive fibre is relatively costly compared with non-conductive fibre, in practice, for many applications, a small amount of accuracy in the measurement of current may be sacrificed in the interest of low cost, by reducing the relative conductivity in the direction perpendicular to current flow.

An arrangement for anisotropic conductivity is shown in *Figure 4*. Outer layer **103** includes conductive fibres **402** that conduct in the direction of the current flowing from connector **111** to connector **112**. Cross threads **401** conduct in a direction perpendicular to this one, and have the effect of ensuring a linear voltage gradient across the sheet, even when variations in connections between lateral fibres **402** with the conductors **111** and **112** are variable, as would be expected in a manufacturing process. Insulating fibres **405** are used between the conductive fibres **402** and **401**. Anisotropic conductivity is achieved, in the present embodiment, by selecting a different ratio of conductive fibres **401** and **402** to non-conductive fibres **405** for each of the warp and weft directions. Thus, in the direction of current flow, which is horizontal in the drawing of plane **103** shown in *Figure 4*, an insulating fibre alternates with a conducting fibre **402**. There is an equal quantity of both. However, in the perpendicular direction, there are two conducting fibres **401** for each insulating fibre **405**. Thus, in the direction perpendicular to applied current flow, or the direction perpendicular to the voltage gradient, conductivity is increased. This has advantages in reducing undesirable current flow when pressure is applied to an area of the sensor, thus

facilitating greater accuracy of measurements.

A similar arrangement is shown for outer plane **102**, also shown in *Figure 4*, with the dimensions rotated by ninety degrees for this plane. By obtaining anisotropic characteristics for both outer planes, overall characteristics are improved. Anisotropic conductivity of the outer planes **102** and **103** is further combined with a relatively high resistivity of the central layer **104**, to obtain the most ideal characteristics.

An advantageous characteristic is obtained for current measurement when the resistance across the thickness of the central layer **104** is significantly higher than the sheet resistance of either of the outer planes **102** and **103**. This advantage arises from the fact that conduction in the central layer is reduced, compared to conduction in the outer planes **102** and **103**, and thereby minimising area and or pressure measurement distortions due to variations in x and y position.

The current flow is further illustrated in *Figure 6*. Where the resistance of the contact region **521** is represented by variable resistor **601**. Since the resistivity of the planes **102** and **103** is approximately constant, a value approximately proportional to Rv, the variable resistance **601**, can be obtained using the relationship illustrated at **611**, where Vout1 is the value obtained by the Analogue to Digital converter in interface **121** at step #2 of the measurement cycle, Vout2 is the value obtained at step #4, and C is related to the resistivity of the fabric planes **102** and **103**. In addition C varies with the area of the contact region **521**.

Thus, for certain constructions of fabric planes **102** and **103**, since the combined resistance of **511**, **512**, **513** and **514** are roughly constant, with small variations in relation to variations in the area of the mechanical interaction, the value obtained at **611** may be taken to be roughly inversely

proportional to the current flowing through Rv, representing the contact region **521**, and will not vary significantly with variation of the position of the mechanical interaction.

The relationships identified at **610** and **611** provide a means for obtaining a value related to the product of force with area. The graph at **620** indicates practical measurements of current i, obtained when an increasing force is applied to a constant area of the sensor **101**. At low levels of applied force, no current flows. At **621** a threshold region is entered, at which the relationship between current and applied force may be non-linear. Thereafter, at **622**, a substantially linear relationship is observed. At **623**, a force has been reached at the limit of the compressibility of the central layer **104**, such that substantial additional force does not result in a corresponding increase in current flow, as illustrated by the substantially flat region of the graph at **624**. A graph of this type may be observed for a wide variety of sensor materials and constructions. However, the gradient **622** and the locations of the non-linear transition regions, and their relative magnitudes, will vary widely, depending on the precise construction of the sensor, and in particular, the construction of the central partially conductive layer **104**.

Figure 7 details an aspect of the present invention that has not been hitherto described, and which affects the ability to use the sensor in conditions where folding of the sensor is likely to occur during its use, or as a result of the shape around which it may be formed. The central partially conductive layer **104** facilitates conduction in such a way that folding is unlikely to result in false conduction at a point where external pressure is not being locally applied. In *Figure 7*, a force **711** is applied locally to the sensor **101**. The sensor is folded, and at places where a fold occurs, such as **722**, the central layer **104** tends to make contact with either the upper plane **102**

or the lower plane **103**, and not with both planes simultaneously. The central layer **104**, does not conduct in the x or y dimensions, and therefore does not allow a connection made at **722** to interfere electrically with connections made at **721**. Furthermore, folds resulting in connection between the central layer **104** and either of the outer planes **102** or **103**, do not result in conduction across the layers. Furthermore, an applied force **711** may be detected with the same accuracy as would be the case if the sensor was completely flat.

Thus, the central layer **104**, being partially conductive, facilitates folding of a fabric based sensor without reduction in accuracy of electrical sensing of a mechanical interaction, and without unwanted outputs related to internal pressures applied resulting from folding or creasing. Preferably the central layer **104** does not significantly conduct across its plane, but conducts significantly in a direction perpendicular to its planarity, when a force is applied to it.

A further embodiment of the present invention is illustrated at *Figure 8*. In *Figure 8* the sensor **101** has a modified construction, wherein the central layer **104** is constructed in a manner different to that shown in *Figure 4*. In this embodiment, the central layer **104** comprises a substantially compressible partially conductive medium, such that changes in applied force result in a larger linear region **622** of the output response, than that which results from use of the sensor detailed in *Figure 4*. The highly compressible medium consists of a foam or compressible knitted or felted fabric having a substrate that is comprised of an insulating material. Within the insulting structure so formed, conductive particles or short filaments are interspersed at regular or random intervals, depending upon the mode of manufacture. Preferably, when no pressure is applied, filaments do not connect with each

other, and so no electrical conductivity is observed in any dimension. As force is applied, however, the structure distorts such that filaments are brought closer together, such that, on average, a certain proportion of filaments connect. The number of connections increases, as the structure is distorted under pressure, as the distance between adjacent filaments is reduced still further. A point is reached at which the medium cannot be compressed further, marking the region from **623** to **624** shown in the graph in *Figure 6*. Connections between filaments are made in the area of the applied force, so that conduction in other areas outside from the region of the applied force remains at zero.

Furthermore, in addition to desirable electrical qualities, a highly compressible medium provides valuable aesthetic qualities in terms of the touch and feel of the sensor as it is being operated.

The highly compressible central layer **104** shown in *Figure 8* results in a detector that is highly linear to the measurement of either applied force over constant area, or area of applied constant pressure. The previous sensor detailed in *Figure 4* is less responsive to variations in force, and can be constructed in such a way that there is very little compressibility or variation in conduction in response to applied pressure. This can be achieved by making each of the conductive regions **411** out of a substantially incompressible material, such as a substantially rigid conductive plastic. With such an arrangement, connection between the outer planes **102** and **103** is substantially on or off, with regard to each individual conductive region **411**.

This type of arrangement is illustrated in *Figure 9*. At graph **910**, a highly non-linear transition between an off state **911** and an on state **913** is observed. There is still a non-vertical gradient **912**, but this is extremely short. Increased applied pressure mostly results in negligible increase in current

flow, as indicated at **914**. At graph **920**, a highly linear variation **922** results in the area of an applied force being changed. Substantially the same relationship is observable even with a substantial variation in applied force. Typically, as the area of an applied force increases, the pressure reduces if the same force is applied over a wider area. Usually, there is a variation over time. With this sensor, only variations in the area makes a substantial difference to the current that is flowing, provided that the force applied uniquely to each individual conductive element **411**, is great enough for local conduction to enter the saturated region **914**. For a very small area, where only two or three conductive elements are receiving significant pressure, there will be a non-linear variation until area is increased to include more conductive elements. This is represented by the non-linearity shown at **921**. As more and more elements are introduced, this non-linearity becomes trivial. This source of inaccuracy can be reduced to tolerable levels by selecting a suitably small size of conductive element **411**.

The relationships for the sensor constructed using the highly compressible central layer shown in *Figure 8* are detailed in *Figure 10*. At graph **1010** a substantially linear relationship is exhibited for pressure applied over a constant area. At graph **1020**, a linear relationship is also exhibited. Unlike graph **920** in *Figure 9*, however, graph **1020** is for area with a constant applied pressure. If pressure changes, so does the current.

A sensor and method for detecting force and area separately are illustrated in *Figure 11*. A sensor **1101** has a multi-layer construction. In effect, two sensors are combined. A first, comprising the arrangement shown in *Figure 4* using substantially incompressible elements **411**, and a second utilising the highly compressible central layer indicated in *Figure 8*. A lower outer plane **1102** makes partial physical contact with a first central layer

1103, constructed in accordance with the central layer shown in *Figures 4* and *7*. The first central layer **1103** makes partial physical contact with a plane **1104**. A compressible medium 1105 forms the next layer, and an outer plane **1106** forms the final stage of the construction. Electrical signals may be applied to layers **1102**, **1104** and **1106**, in order to detect the effect of mechanical interactions with the partially conductive layers **1103** and **1105**. The direction of conductivity across planes **1102** and **1106** is parallel. Conductivity across plane **1104** is perpendicular to that of planes **1102** and **1106**. Using this construction, the characteristics of the two detectors are combined. From a first set of characteristics, detailed in *Figure 9*, an area of applied pressure may be determined. A second set of characteristics, detailed in *Figure 10*, determines a value proportional to the product of force and area. The applied force may then be determined by dividing the second set of characteristics by the first, or a second reading by a first reading. Readings related to force and area are thereby obtained independently, thus also allowing a calculation for pressure, being force divided by area, to be made along with x and y co-ordinates obtained as described previously. In *Figure 11*, a composite graph **1110** shows the combined response of the two sensors. A first curve **1111** indicates the response of the sensor comprising layers **1104**, **1105** and **1106**. A second curve **1112** indicates the response of the sensor comprising layers **1102**, **1103** and **1104**.

Depending on the process of manufacture, it may be possible to obtain a compressible central layer with the lateral insulating characteristics that have been described. However, it may also be advantageous to use a cheaper form of manufacture, in which case desirable characteristics may still be obtained, but with a reduction of insulating characteristics laterally across the plane of the central layer **104**, thus resulting in a possible slight loss of

accuracy when the sensor is folded.

Errors in readings due to creasing and folding may be reduced using a central layer of high lateral sheet resistivity.

As explained earlier, it is possible to construct a central layer having a lateral insulating characteristic, as shown in *Figure 4*, using only small local conductive elements **411**. Alternatively, lateral insulation may be achieved using the compressible medium also described previously. As a further alternative, a structure processing very high sheet resistivity may be used, having a lower resistance across its thickness than laterally. In *Figure 12*, this reduction in accuracy is minimised by additional insulating means **1201**. This is provided between the outer planes **102** and **103** and the central layer **104**. The additional insulating means may be a separate layer in itself, such as an insulating mesh or weave. Alternatively, the recessing of the conductive inner surface of the outer planes **102** and **103**, or of the central layer **104**, may be achieved by a process of combining conductive fibres of a smaller diameter with non-conductive fibres having a greater diameter. Using this type of arrangement, the requirement that the central layer **104** should be laterally insulating is reduced, and so the cost of manufacture may be reduced.

Figure 12 shows that conduction between a connection resulting from folding at **1212**, does not interfere with the force applied at **1211**, due to the presence of insulating means **1201**. Furthermore, other folding elsewhere does not interfere with detection of mechanical interaction, due to the fact that, at no point due to folding, is a connection made between the central layer and both the outer layers **102** and **103** in the same region. In *Figure 13*, for example, multiple folds and creasing are observed. A particularly deep crease is seen at **1301**, where the central layer makes electrical contact with the outer plane **102**. However, at the same point **1301**, the lower plane **103** is

insulated from the central layer by the insulating means.

At location **1301**, the insulating means prevents a large area of electrical contact between the inner layer **104** and the lower outer plane **103**. Thus, although lateral conduction between the creases at locations **1301** and **1302** may occur in the central layer itself, the presence of the insulator at **1302** and elsewhere, prevents simultaneous contact with both of the outer planes in any given region. In this way, provided that the lateral conductivity of the central layer **104** is sufficiently high, the lateral conductivity of the central layer does not significantly interfere with signals generated as a result of a deliberate mechanical interaction, such as that indicated at **1211** in *Figure 12*. *Figure 13* shows that, for a sensor using a laterally conductive central layer **104**, current may flow between upper and lower conductive layers **102** and **103** as a result of creasing and folding alone. However, provided the lateral resistivity or sheet resistance of **104** is high, this current may be negligible for many applications, and there may be cost advantages in the use of such a structure.

The structure of the position sensor as described makes possible construction of a flexible sensor from fabric, including the possibility that the sensor may be folded and creased in the way that is to be generally expected of fabrics.

As an alternative to the circuit shown in *Figure 2*, interface circuitry shown in *Figure 14* is provided to enhance the performance of a fabric sensor of the type that has been described. Furthermore, additional calibration circuitry may be included in order to compensate for change in resistance due to stretching, humidity or temperature.

In *Figure 14*, a constant current source **1401** supplies a substantially constant current to the fabric-based position sensor **101** via a first connection

107. Additional connections are made to the sensor using the connections shown in *Figure 1*, which are the other connection **108** to the upper plane **102**, and the two connections **111** and **112** to lower plane **103**. Connection between outer planes **102** and **103** via the central layer **104** may be considered as forming a variable resistor when a force is applied.

A first differential amplifier **1403** measures the voltage between the connections **107** and **108** of the upper plane **102**. A second differential amplifier **1404** measures the voltage across connections **108** and **112**, and a third differential amplifier measures the voltage across the connections **112** and **111**. Terminal **111** is connected to ground, and provides a current sink for the current source **1401**, when enough pressure is applied to the sensor to enable current to flow from the upper plane **102** to the lower plane **103** via the central layer **104**.

In operation, when a current is flowing through the sensor **101**, a voltage drop exists across the top plane **102**, in the direction from connector **107**, towards the region of the applied force. Current then flows through the central layer **104** in the region of the applied force. Thus, the remainder of the top plane **102** does not sustain any voltage drop, and the potential at the region of mechanical interaction is measurable at terminal **108**. The voltage measured between terminals **107** and **108** therefore gives an indication of the position across the top plane **102** of the region of mechanical interaction.

A similar effect operates in the lower plane **103**. Conduction of current from the region of mechanical interaction to terminal **111** results in a voltage being developed across this region. As no current is conducted from the region of mechanical interaction to connector **112**, the potential at connection **112** is the same as that developed at the region of mechanical interaction. The voltage measured between connections **111** and **112** provides an

indication of the location of the region of mechanical interaction across the lower plane **103**, in a direction perpendicular to that indicated by the voltage between connections **107** and **108**.

Furthermore, the potential developed across the variable resistance that results from a force being applied to a region of the sensor is measurable between connections **108** and **112**, and this voltage reduces as the electrical resistance of the region under pressure is reduced.

The arrangement shown in *Figure 14* facilitates continuous measurements to be made of both x and y position, along with a measure of the voltage developed across the central layer **104**. The voltage across the central layer may be used to determine pressure and or area of the region of mechanical interaction, using techniques previously described in relation to current measurement. However, in the case of the circuit shown in *Figure 14*, the same calculations are performed with respect to a voltage, while the current is constant. In the previous descriptions of pressure and or area measurement, it is assumed that voltage is maintained as a constant (or determined and then factored out of the equations), and that current was the characteristic that varied. Either form may be used, with minor adjustments to the equations required in order to determine the actual physical characteristics of the mechanical interaction.

The differential amplifiers **1403**, **1404** and **1405** provide amplification and high impedance buffering for the three voltage measurements that are made across the sensor. The outputs from these three amplifiers are supplied to an analogue multiplexer circuit **1407**. The multiplexer selects one of the three voltages to be supplied to an analogue to digital (A-D) converter **1406**. The output of the analogue to digital converter **1406** is a twelve bit binary value providing an indication of the voltage that has been measured.

This is supplied to a micro-controller **1402**.

The sequence executed by the micro-controller is substantially similar to that identified for the voltage measuring circuit shown in *Figure 2*, and detailed in *Figure 3*. At step **301**, the micro-controller enters a wait state, possibly enabling a reduced power consumption. At step **302** a reading is obtained from the A-D converter **1406**, and this is stored in registers inside the micro-controller. At step **303** conversion calculations are performed, and at step **304** information registers are updated as a result of calculations performed at step **303**.

For the circuit of *Figure 14*, step **305** is different, in that one of the three differential amplifiers is selected for connection to the A-D converter for voltage measurement. This is performed by a binary control signal output on lines C1 and C2 of the micro-controller. With C1 and C2 both at 0V, differential amplifier **1403** is selected. With C1 and C2 at 5V and 0V respectively, differential amplifier **1404** is selected. With C1 and C2 at 0V and 5V respectively, differential amplifier **1405** is selected. One of these three conditions is selected at step **305**, and at step **306** electrical conditions are allowed to settle and the micro-controller then waits for the next timer interrupt before a measurement is made of the selected voltage.

Constant current source **1401** is a low cost part, such as an LM334H, which is manufactured by SGS Thompson. The precise current from this part, and also other characteristics of the circuit that are assumed to remain constant, may be difficult to determine as it may vary according to manufacturing tolerances, or during use in response to temperature, humidity and other environmental variations. Characteristics of these variations are taken into account by calibration circuitry, comprising a calibration resistor **1451** and a CMOS switch 1408. This circuit is used while the sensor is not

conducting. The micro-controller is able to close the CMOS switch **1408** by setting control line C0 to 5V. Thereafter, current flows through the calibration resistor **1451**.

Provided that no current is flowing through the central layer of the position sensor **101**, the current flowing through the resistor is the same as the current that will flow through the sensor when a force is applied to the sensor to cause conduction through the central layer **104**. Because the resistance value of the calibration resistor is known, and this does not change significantly due to temperature or other environmental characteristics, the current through it may be determined by measuring the voltage across it, as performed by differential amplifier **1404**.

Furthermore, it is possible to obtain resistance measurements for the outer planes **102** and **103**, as this same current is now flowing entirely across both these planes. The voltage developed across connections **107** and **108**, under these conditions, is the maximum voltage that can be generated from this plane **102** as a result of mechanical interactions. The minimum voltage is always zero. Thus, during calibration, the voltage measured by amplifier **1403** determines a scaling factor to be used whenever the position of a mechanical interaction is determined with respect to the top plane **102**. Similarly, the lower plane **103** may be calibrated in this way, with the full range being defined by a minimum of zero volts, to a maximum defined by the voltage measured across connections **111** and **112** during calibration. This provides highly accurate calibration data, that may be used to determine position measurements with a high degree of accuracy, and with a highly simplified and low cost circuit.

In an alternative embodiment, the calibration resistor **1451** is excluded, and simply replaced by a link. Thus, when switch **1408** is

conducting, current flows directly from connection **108** to connection **112**. The voltages developed across planes **107** and **108** are unaffected by this modification.

The absolute value of the constant current generated by the constant current source itself is not required as a measurement. It is the ratio of the current through the calibration resistor **1451**, to the voltages that are measured during sensor operation, that enables environmental factors and manufacturing variations to be counteracted. Since the current is determined by measuring the voltage across the calibration resistor, this calibration voltage is all that is required in subsequent calculations to determine the characteristics of mechanical interactions. The constant current emitted by the current source **1401** itself, need only fall within bounds of viable circuit operation, and thus a reasonable manufacturing variation in this value may be accounted for by use of this type of circuit. Typically, x position may be calculated using the measured reading for the position with the calibration resistor switched out divided by the last calibration reading representing maximum x. Y position may be calculated in a similar way. Similarly z reading related to force and area may be calculated using the measured reading for Rv, or the contact resistance, divided by the last available reading of voltage across the calibration resistor.

The micro-controller may perform a calibration cycle periodically, for example, once every second, depending on how quickly the environment is expected to change. In some applications, calibration need only be performed once when the system is powered up, and perhaps once every hour or day thereafter.

Alternatively, the micro-controller may cause the circuit to remain in calibration mode, and to monitor the voltage across the calibration resistor

continuously. A sharp change in voltage indicates that a non-environmental change has occurred, due probably to conduction of the sensor via its central layer **104**. When a sharp change of this kind is observed, the micro-controller ends calibration, and performs position measurements as described above. The calibration value used is the same value as was observed continuously prior to the sharp change. Signal processing methods may be applied both to determine the relatively constant calibration voltage across the resistor **1451**, and to determine a rate of change indicative of sensor activation. For example, a kalman filter may be used to determine the steady state calibration voltage, and comparisons between the output from the kalman filter and the instantaneous voltage across the resistor **1451** may be used to determine whether or not the sensor has been activated. Once the sensor is no longer conducting, calibration may be selected again.

In an alternative embodiment, the circuit of *Figure 14* is modified to include additional CMOS switches controlled by the micro-controller **1402**, such that the connections **107** and **108** are swapped, and connections **111** and **112** are swapped. After these connections have been swapped, current flows through the previously non-current carrying regions of the sensor planes **102** and **103**. Measurements made in this way, with the calibration circuit switched off, may be combined with measurements made in the unswapped condition, in order to improve the overall accuracy of measurements.

The multiplexer circuit **1407** is a generic CMOS **4053** integrated circuit. The micro-controller **1402** is an 80C51, manufactured by Phillips. However, in an alternative embodiment, a PIC type micro-controller may be used, as manufactured by Microchip. A part may be used that includes the A-D converter **1406**, thereby reducing the unit cost of high volume manufacture.

The micro-controller communicates with a computer **132** shown in *Figure 1* via a serial connection **131**, or other information receiving device, to which measurements are to be supplied.

The combined sensor shown in *Figure 11* may be used with a modified version of the circuit shown in *Figure 14*. In this arrangement, the lower plane **1404** of the top sensor is also the top plane **1404** of the lower sensor. Under the application of a force, conduction occurs through the central layers **1105** and **1103** of both sensors, through the common plane **1104**. A potential developed at plane **1104** may be measured by a single connection made to it, and from this potential, the voltages sustained across the central layers **1103** and **1105** may be independently identified. Voltages sustained as a result of current flow across the top plane **1106**, to determine x position, and lower plane **1102**, to determine y position, may be made in the manner previously described for a constant current measuring system in a single sensor. An implementation of this arrangement requires only an additional differential amplifier and connection to the multiplexer **1407**. Thus, additional layers can be used with minimum complexity of additional control circuitry.

Claims

1. A method of detecting the position of a mechanical interaction in a sensor constructed from fabric, wherein a substantially constant electric current is established through said elements, including steps of

measuring a first electrical potential developed in a first plane in response to said current;

measuring a second electrical potential developed in a second plane in response to said current; and

processing said measurements to identify a position of said mechanical interaction.

2. A method according to claim **1**, including additional steps of:

measuring a third potential developed between said first plane and said second plane; and

processing said third potential to identify an additional characteristic of said mechanical interaction.

3. A method according to claim **1** or claim **2**, including connecting a calibration circuit that provides an alternative route for current flow through said first and second planes.

4. A method according to claim **3**, wherein said calibration circuit facilitates steps of:

identifying a first voltage range in said first plane; and

identifying a second voltage range in said second plane.

5. A method according to claim **4**, wherein said identified ranges are used with at least one of said measured potentials in order to identify a position of a mechanical interaction.

6. A method according to claim **3**, wherein a calibration signal, developed as a result of current flowing through said calibration circuit, is monitored to identify the onset of conduction between said first and second planes as a result of a mechanical interaction.

7. A method according to claim **3**, including the step of:

switching said route of current flow in response to an analysis of sensor conditions.

8. A method according to any of claims **1** to **7**, wherein said first plane has a first and second connection point and said second plane is connectable at third and fourth connection points, further including steps of:

supplying said constant current to said first plane at said first connection point;

sinking said constant current from said second plane at said fourth connection point;

measuring a potential in said sensor;

swapping said first and second connection, and, swapping said third and fourth connections;

repeating the measurement of said potential in said sensor; and

combining said repeated measurements to determine a characteristic of a mechanical interaction in said sensor.

9. In a sensor comprising:

a first outer plane through which a substantially constant current flows to develop a first potential;

an inner plane, which, in combination with said first outer plane, has been constructed substantially to respond to force and area of mechanical interactions;

a second outer plane, through which said constant current also flows to develop a second potential, which, in combination with said inner plane, has been constructed substantially to respond to the area of mechanical interactions;

a method of detecting an indication of applied force of a mechanical interaction, including steps of:

measuring a third potential developed between said first outer plane and said inner plane;

measuring a fourth potential between said inner plane and said second outer plane; and

processing said third potential with said fourth potential to identify an indication of the force of mechanical interactions.

10. A method according to claim **9**, including additional steps of:

processing said first potential to identify a first co-ordinate of said mechanical interaction; and

processing said second potential to identify a second co-ordinate of said mechanical interaction.

11. A position detector constructed from fabric having electrically

conductive elements, comprising at least two electrically conducting planes, wherein

a substantially constant electric current is passed through said planes to determine the position of a mechanical interaction.

12. A position detector according to claim **11**, including measuring a voltage between said planes in order to determine an additional characteristic of said mechanical interaction.

13. Apparatus for measuring characteristics of a mechanical interaction in a position detector constructed from fabric, including

processing means;

constant current means arranged to pass a current through said position detector; and

calibration means arranged to conduct said constant current by an alternative route to that used during position measurement.

14. Apparatus according to claim **13**, wherein said calibration means facilitates steps of:

identifying a first voltage range in said first plane; and

identifying a second voltage range in said second plane.

15. Apparatus according to claim **14**, wherein said processing means is arranged to process said identified ranges with representations of voltages developed in said fabric sensor while said calibration means is inactive.

16. Apparatus according to any of claims **13** to **15**, wherein said processing means is arranged to monitor voltages developed during calibration, thereby to identify:

the onset of conduction between said first and second planes.

17. Apparatus according to any of claims **13** to **16**, wherein said processing means is configured to switch said route of said current flow in response to an analysis of sensor conditions.

18. Apparatus according to any of claims **13** to **17**, wherein said first plane has a first and second connection point and said second plane is connectable at third and fourth connection points, further including switching means controllable to:

supply said constant current to said first plane at said first connection point;

sink said constant current from said second plane at said fourth connection point; and

swap said first and second connection, and, swap said third and fourth connections.

19. A sensor for measuring position and other characteristics of a mechanical interaction, comprising:

a first outer plane through which a substantially constant current may flow to develop a first potential;

an inner plane, which, in combination with said first outer plane, is constructed substantially to respond to the force area product of mechanical interactions;

a second outer plane, through which said constant current also may flow to develop a second potential, which, in combination with said inner plane, is been constructed substantially to respond to the area of mechanical interactions;

means for supplying said constant current to said sensor; and

means for obtaining measurements of said potentials in order to determine position and other characteristics of mechanical interactions.

20. A sensor according to claim **19**, including control circuit means arranged to:

process said first potential to identify a first co-ordinate of said mechanical interaction;

process said second potential to identify a second co-ordinate of said mechanical interaction; and

process said third and fourth potentials to determine other characteristics of said mechanical interaction.

21. A method of detecting the position of a mechanical interaction substantially as herein described with reference to the accompanying drawings.

22. A sensor substantially as herein described with reference to the accompanying drawings.

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Application No: GB 0009676.8 **Examiner:** Eamonn Quirk
Claims searched: 1-12, 19-22 **Date of search:** 22 September 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): G1N(NAQB, NACH, NACNR) H1N(NUJD)

Int Cl (Ed.7): G06K (11/12)

Other: Online: WPI, EPODOC, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A,P	GB 2 341 929 A	(Electrotextiles)	
A	US 5 159 159	(David Asher)	
A	US 5 008 497	(David Asher)	
A	US 4 897 511	(Gunze KK)	
A	EP 0 134 853	(AMP Inc.)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

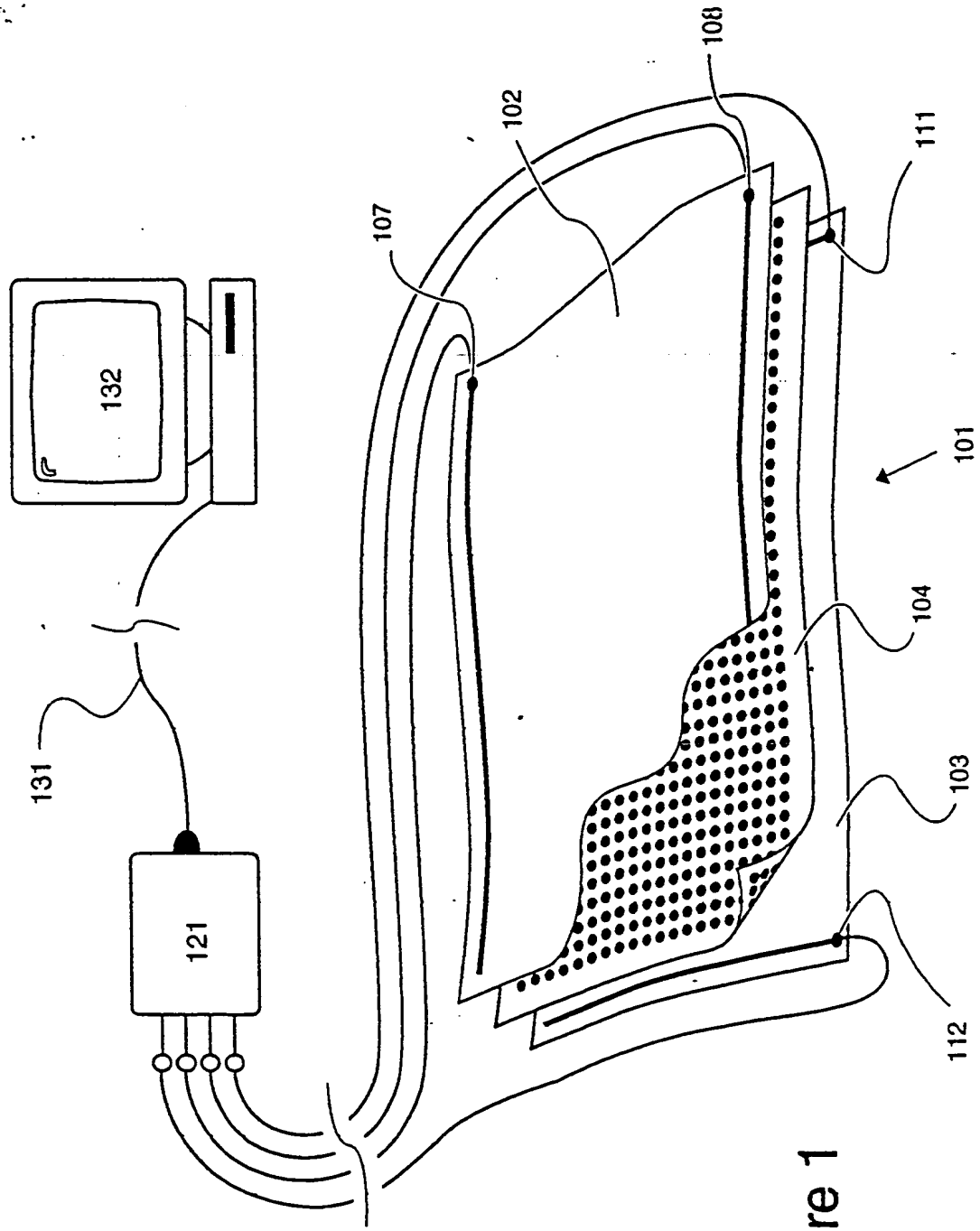


Figure 1

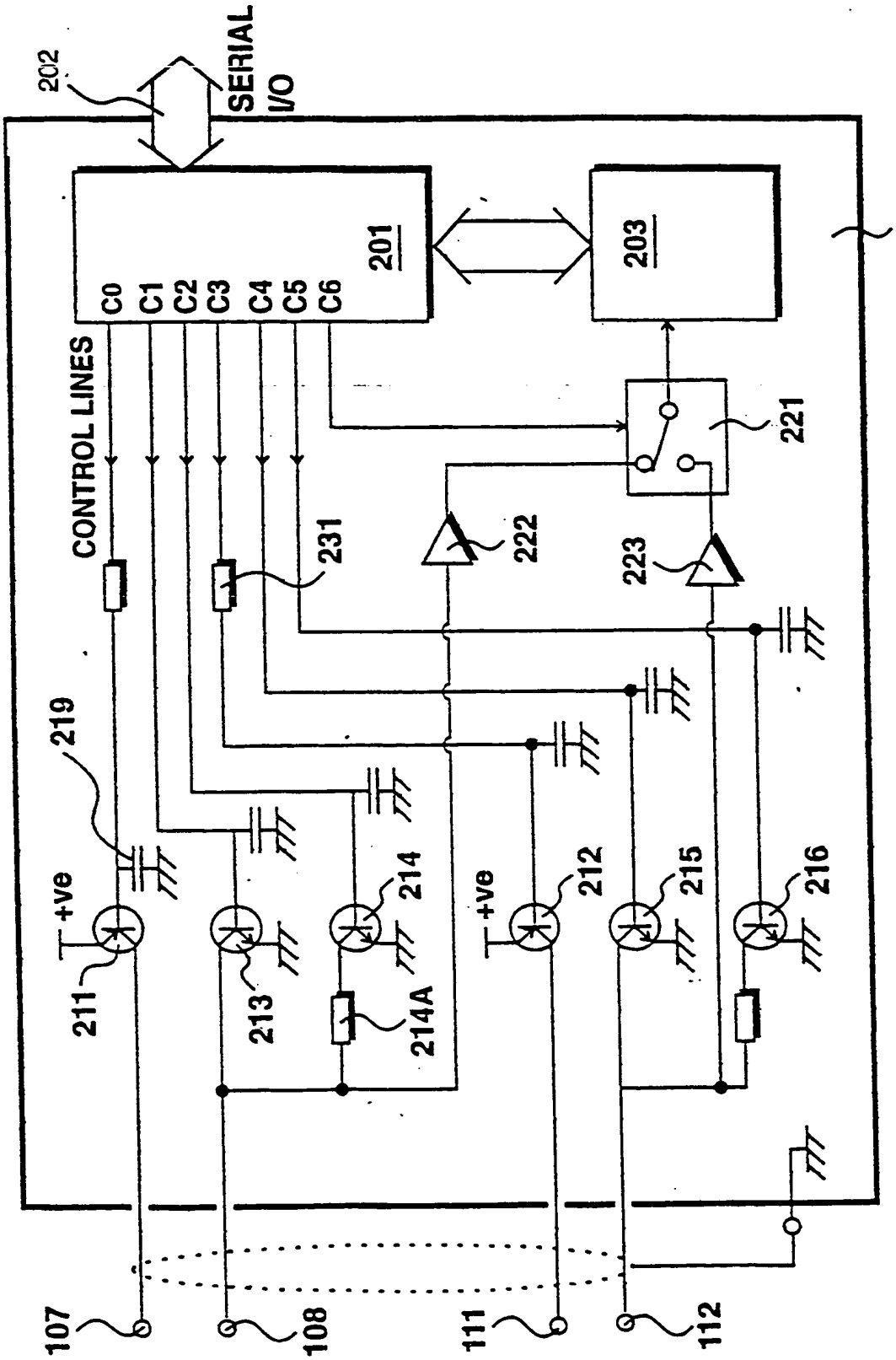
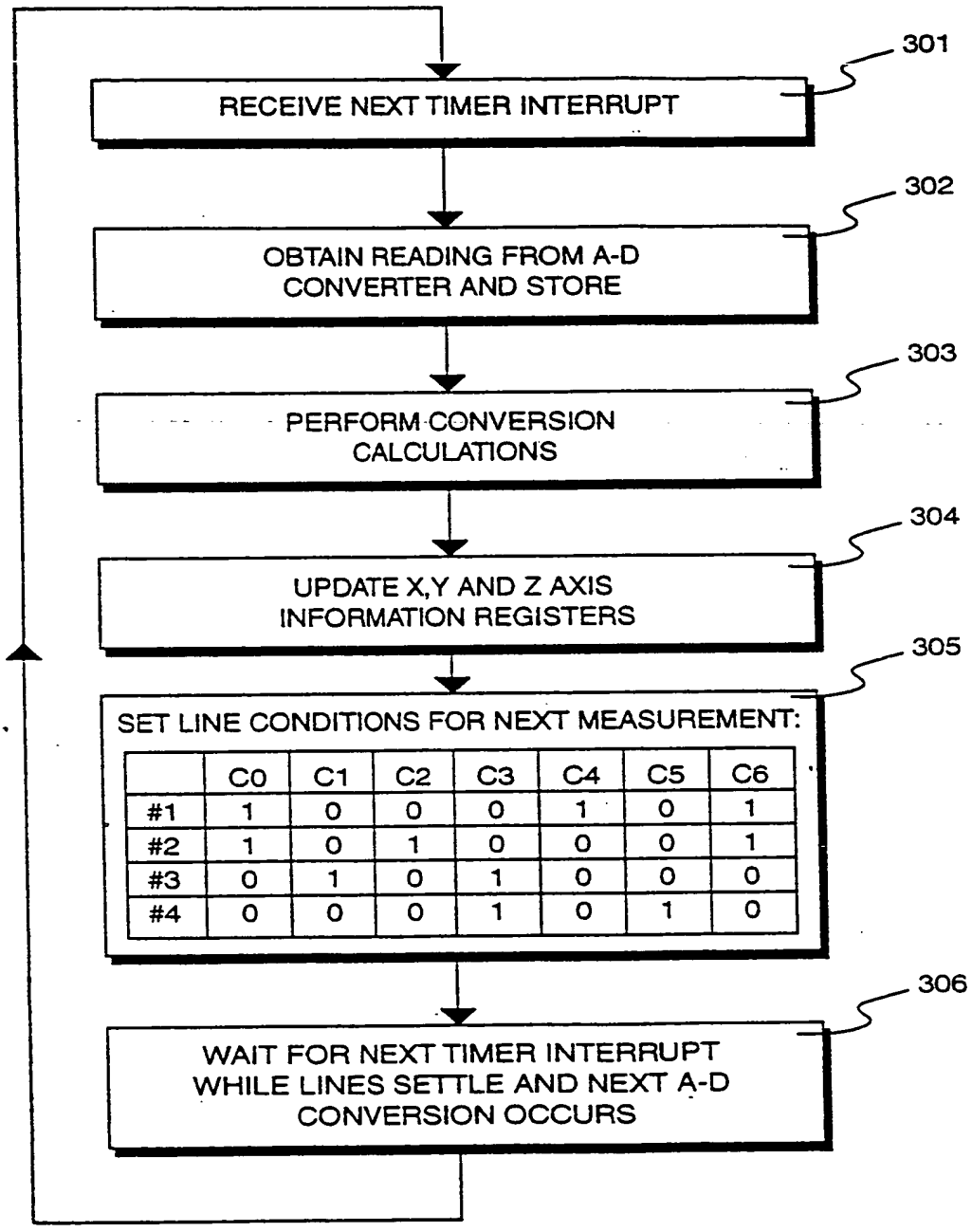
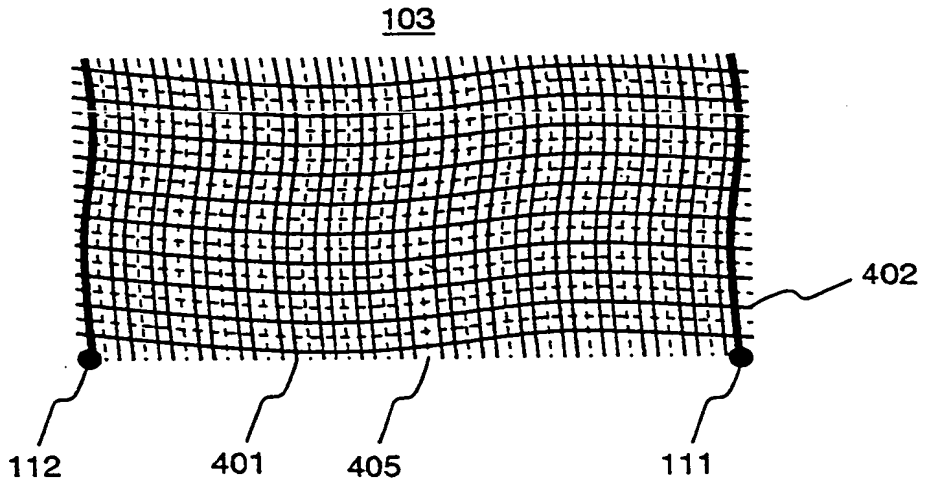

202
SERIAL I/O
201
203
121
C0
C1
C2
C3
C4
C5
C6
CONTROL LINES
221
222
223
231
219
+Ve
211
213
214
214A
+Ve
212
215
216
107
108
111
112

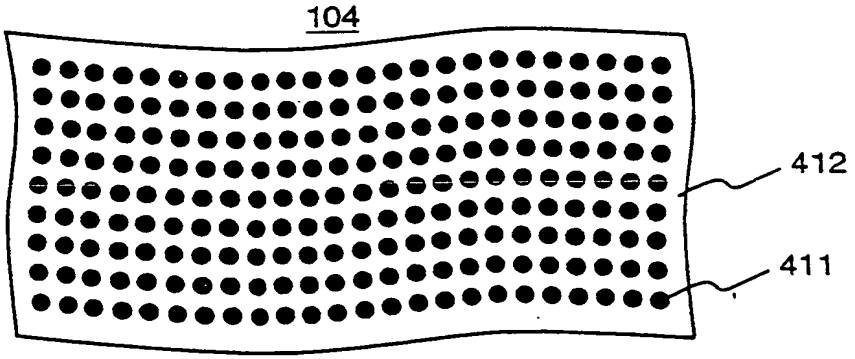
Figure 2



	C0	C1	C2	C3	C4	C5	C6
#1	1	0	0	0	1	0	1
#2	1	0	1	0	0	0	1
#3	0	1	0	1	0	0	0
#4	0	0	0	1	0	1	0

Figure 3





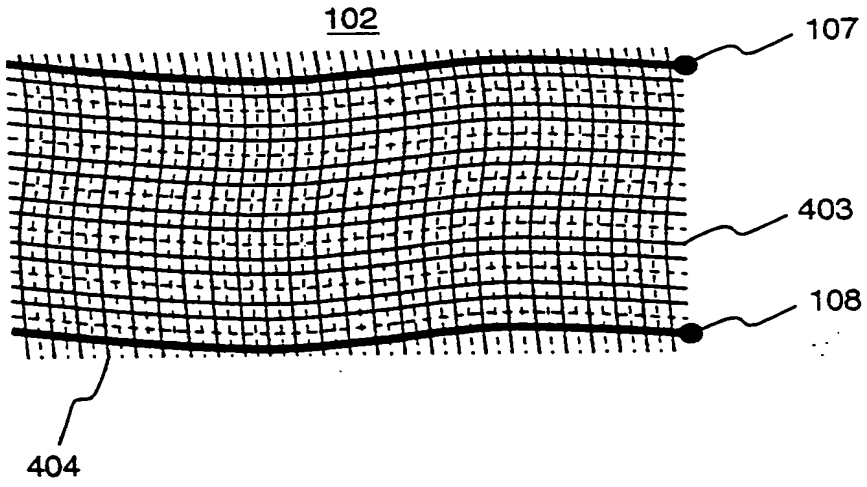


Figure 4

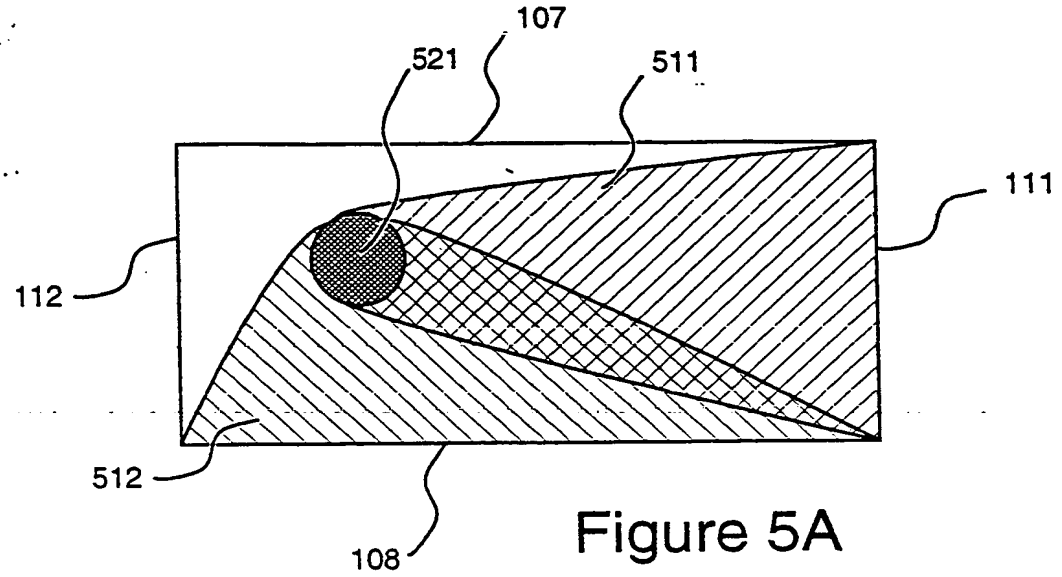


Figure 5A

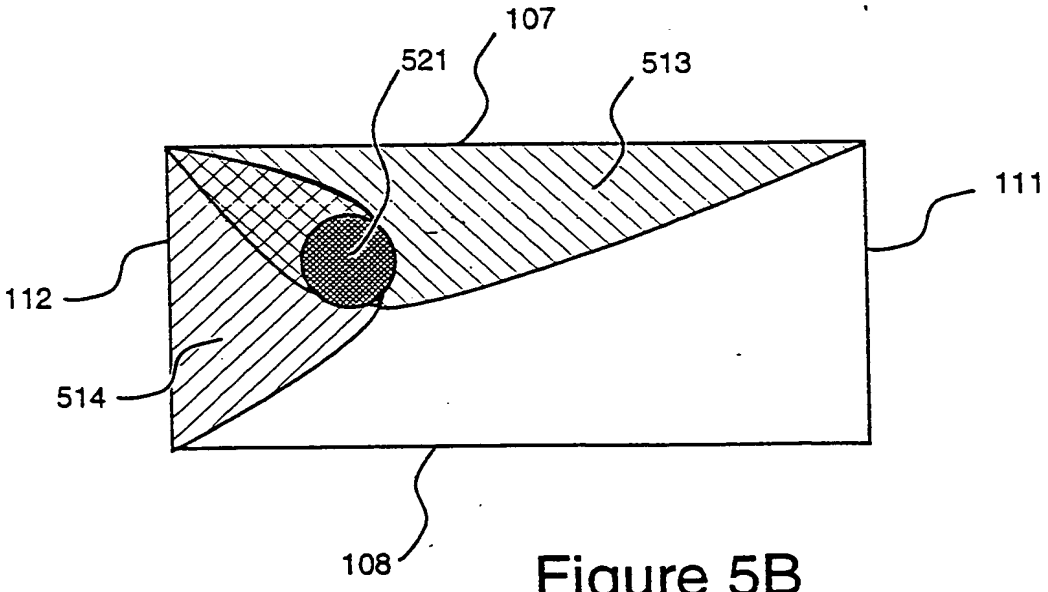
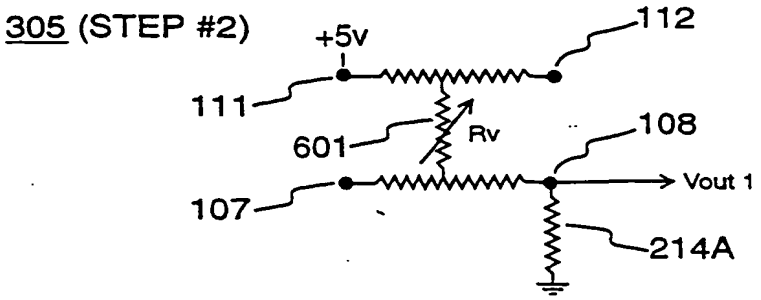
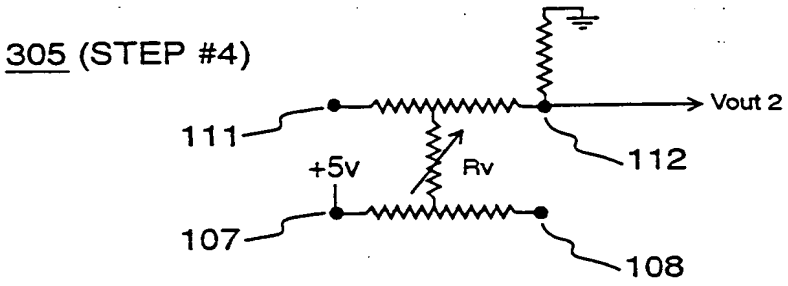


Figure 5B





610

$1/Rv \propto i \sim \propto$ AREA . FORCE

611

$(1/Vout\ 1) + (1/Vout\ 2) \propto Rv + C$

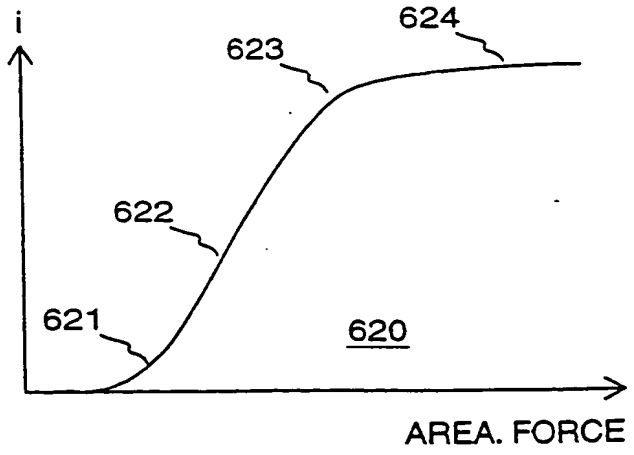


Figure 6

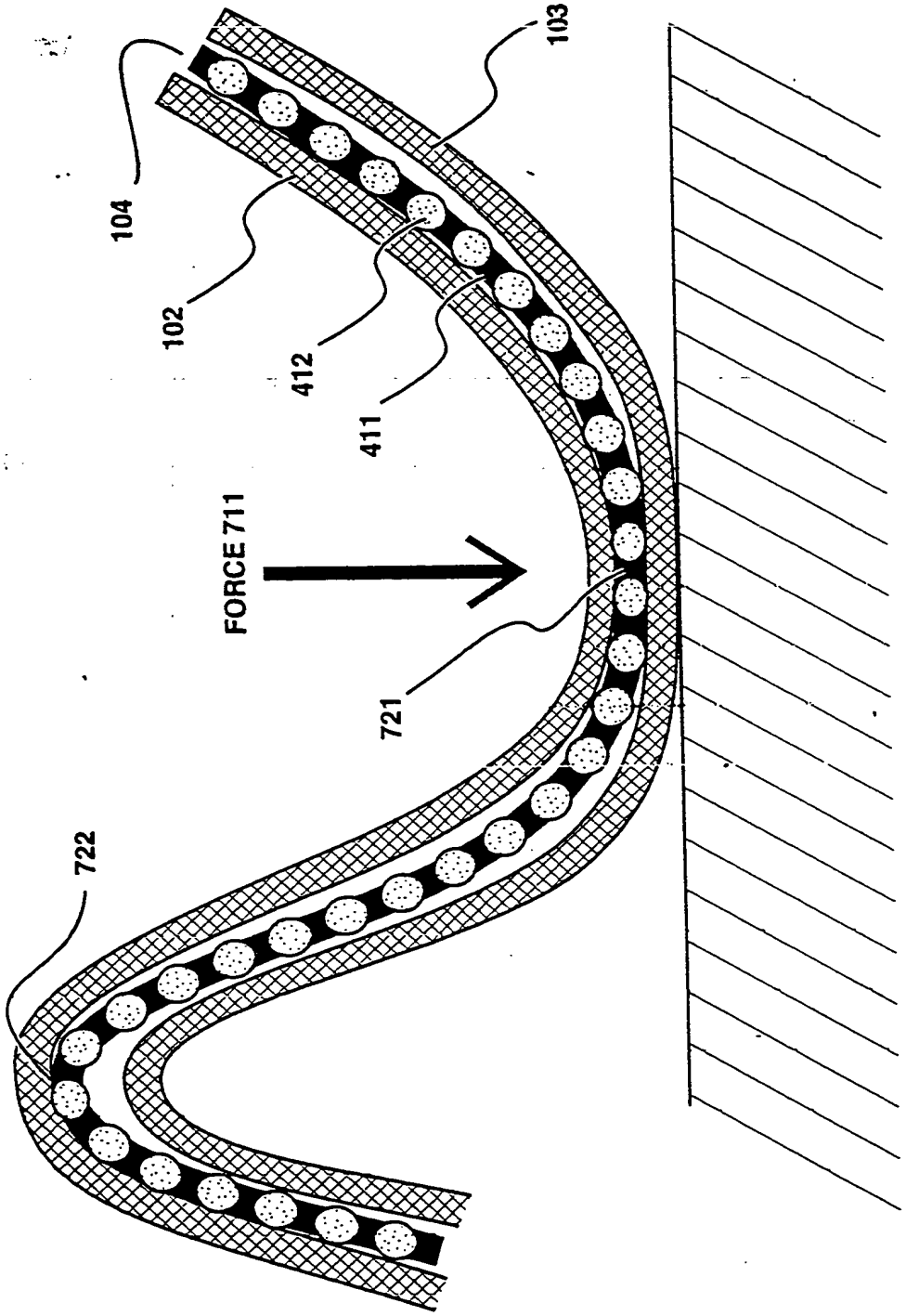


Figure 7

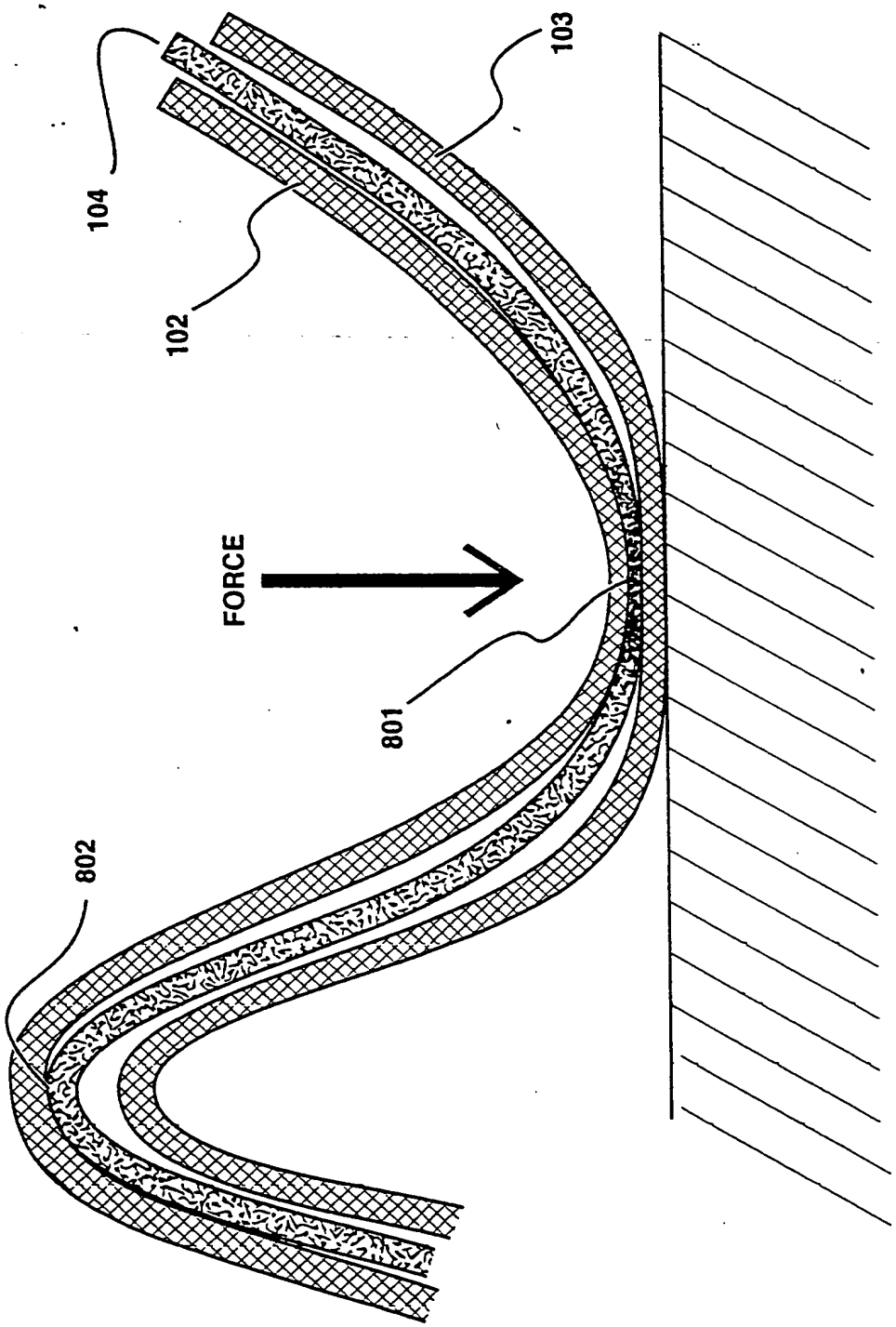


Figure 8

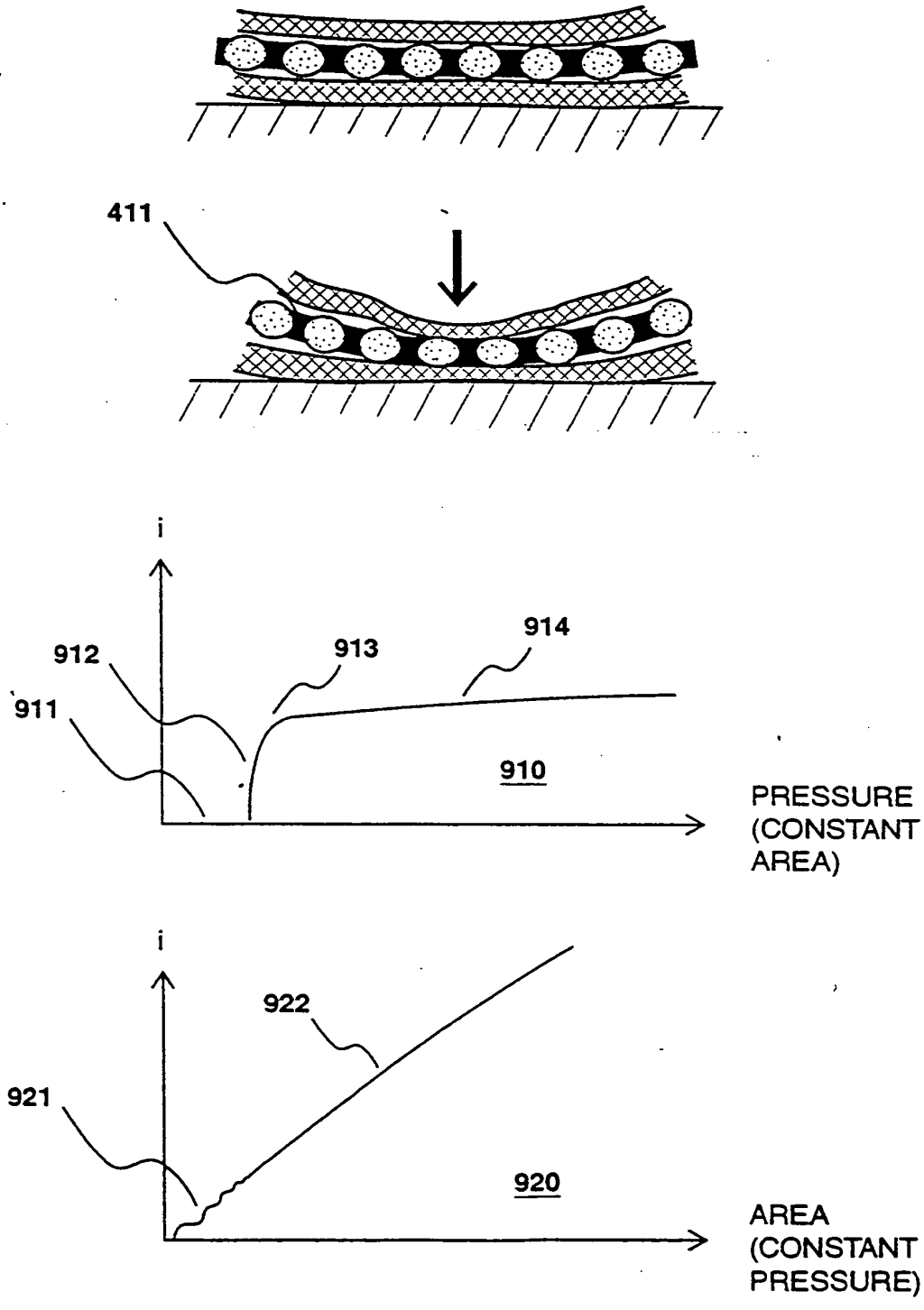

411
i
912
913
914
911
910
PRESSURE
(CONSTANT
AREA)
i
922
921
920
AREA
(CONSTANT
PRESSURE)

Figure 9

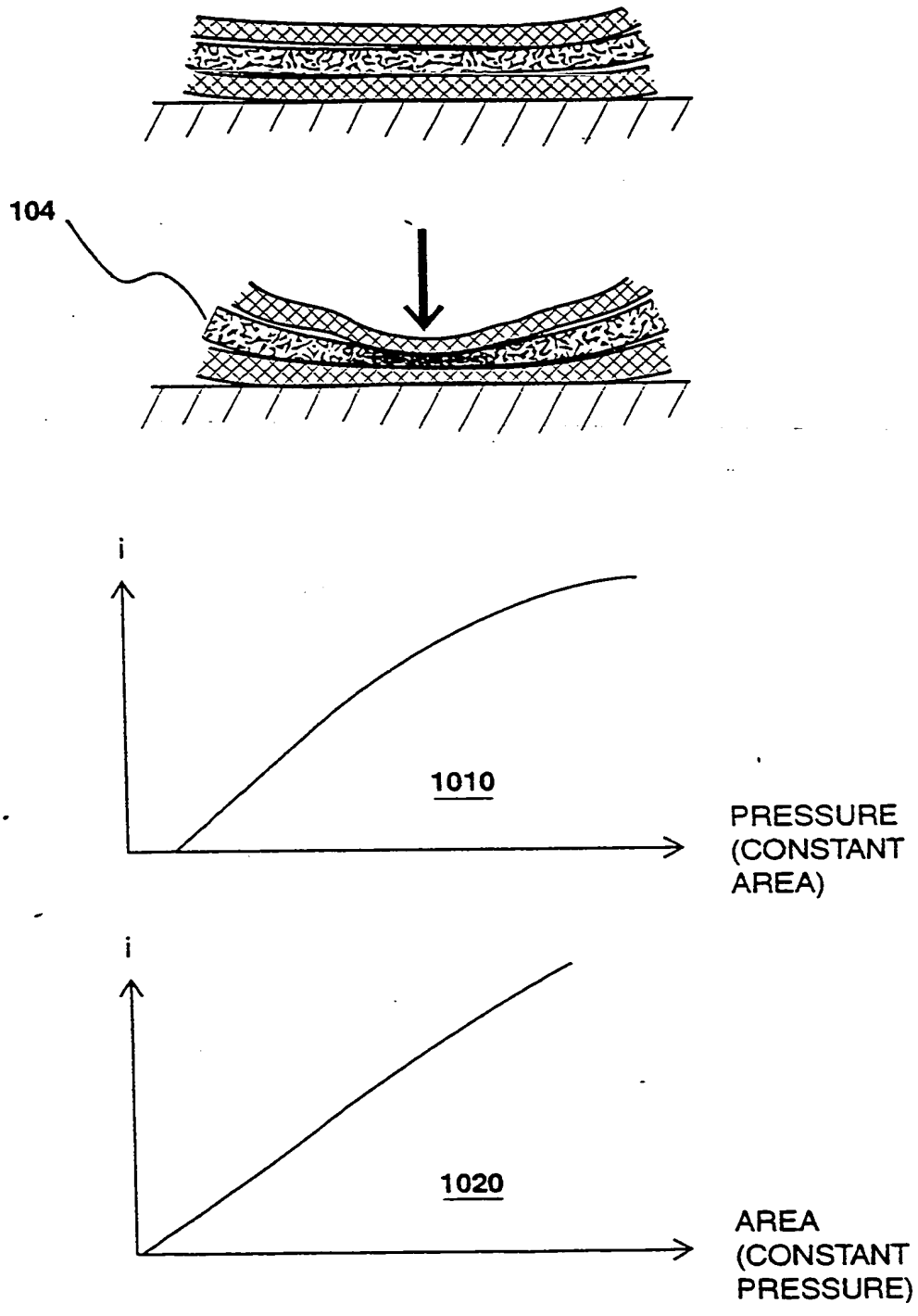
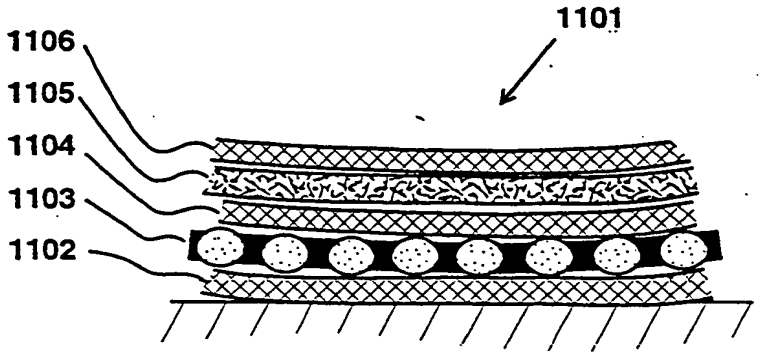

104
i
1010
PRESSURE
(CONSTANT
AREA)
i
1020
AREA
(CONSTANT
PRESSURE)

Figure 10


1101
1106
1105
1104
1103
1102

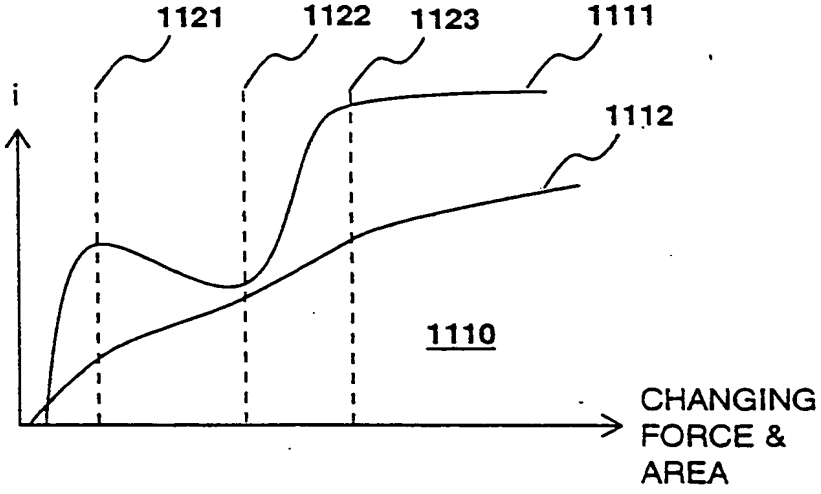

1121
1122
1123
1111
1112
i
1110
CHANGING
FORCE &
AREA

Figure 11

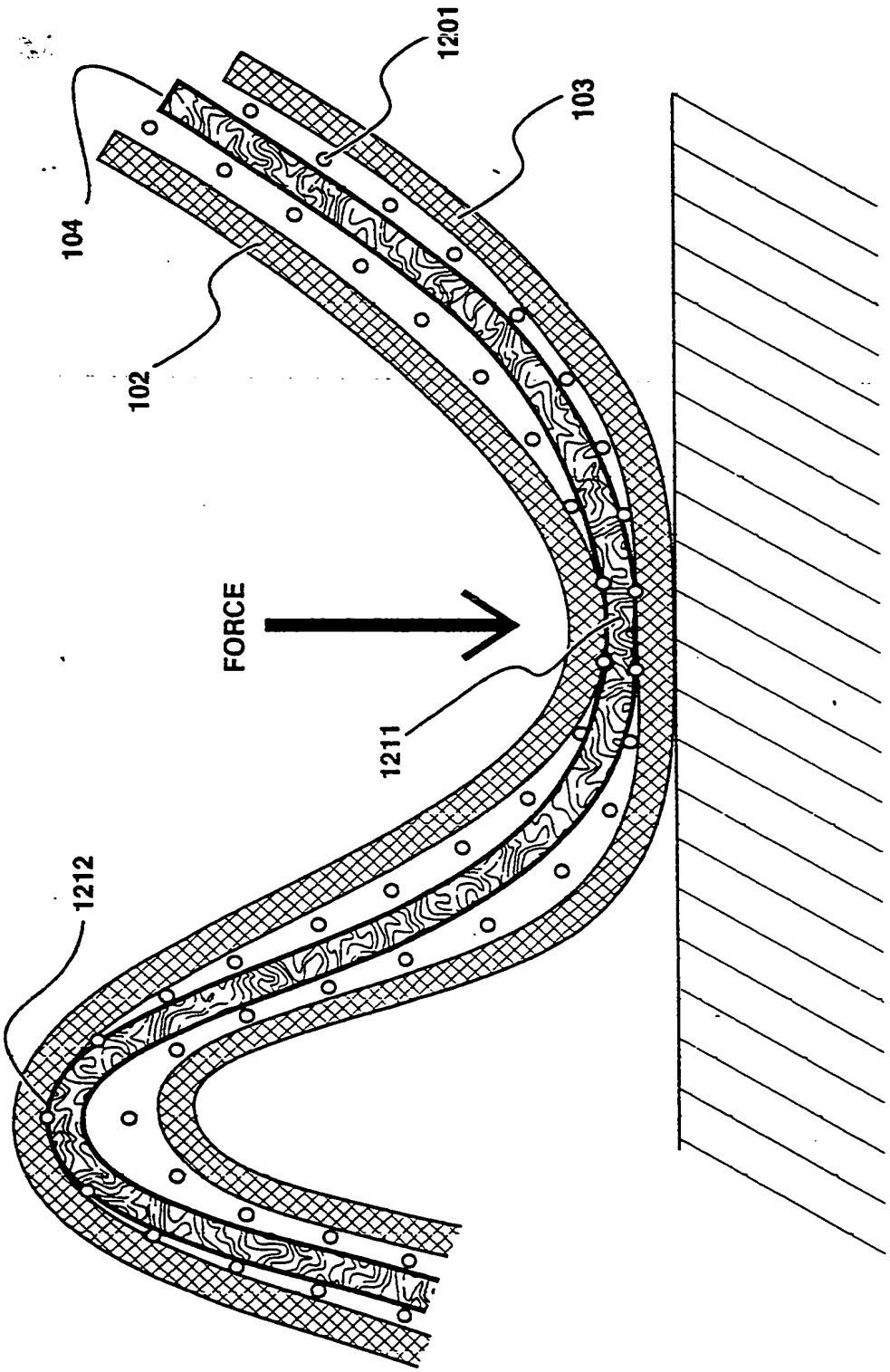


Figure 12

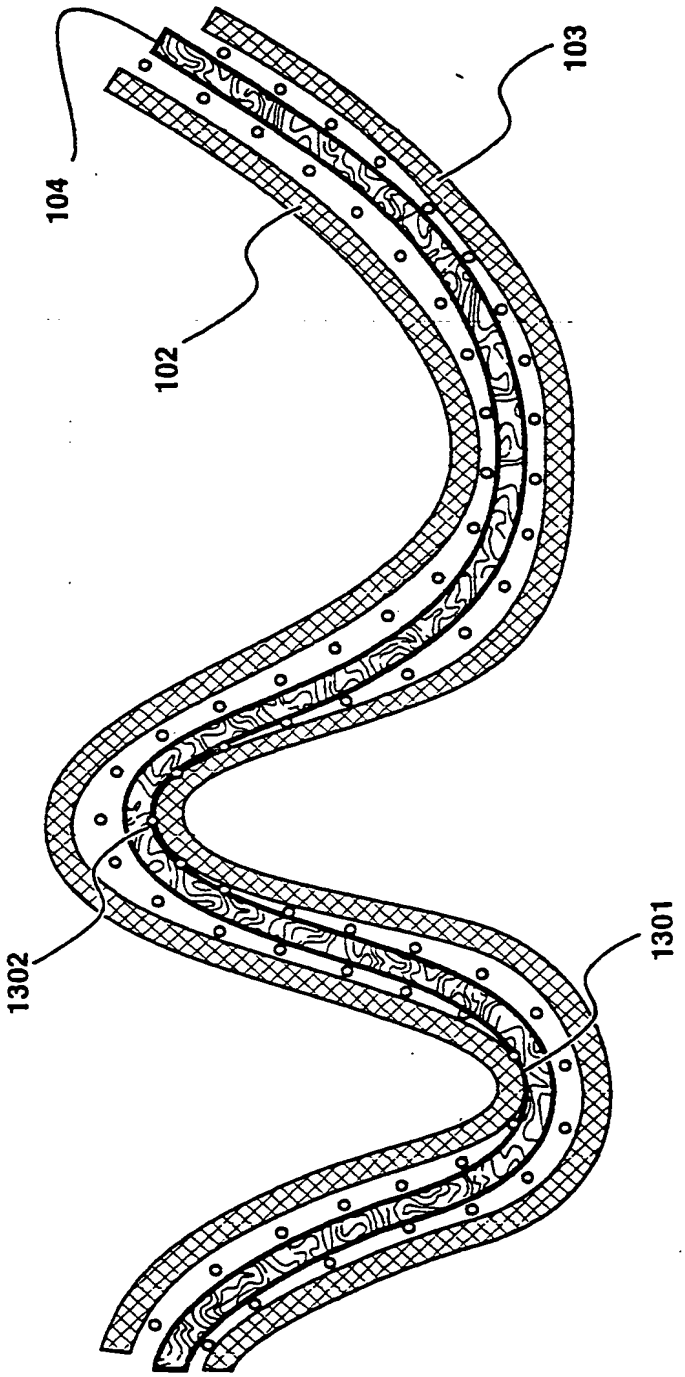


Figure 13

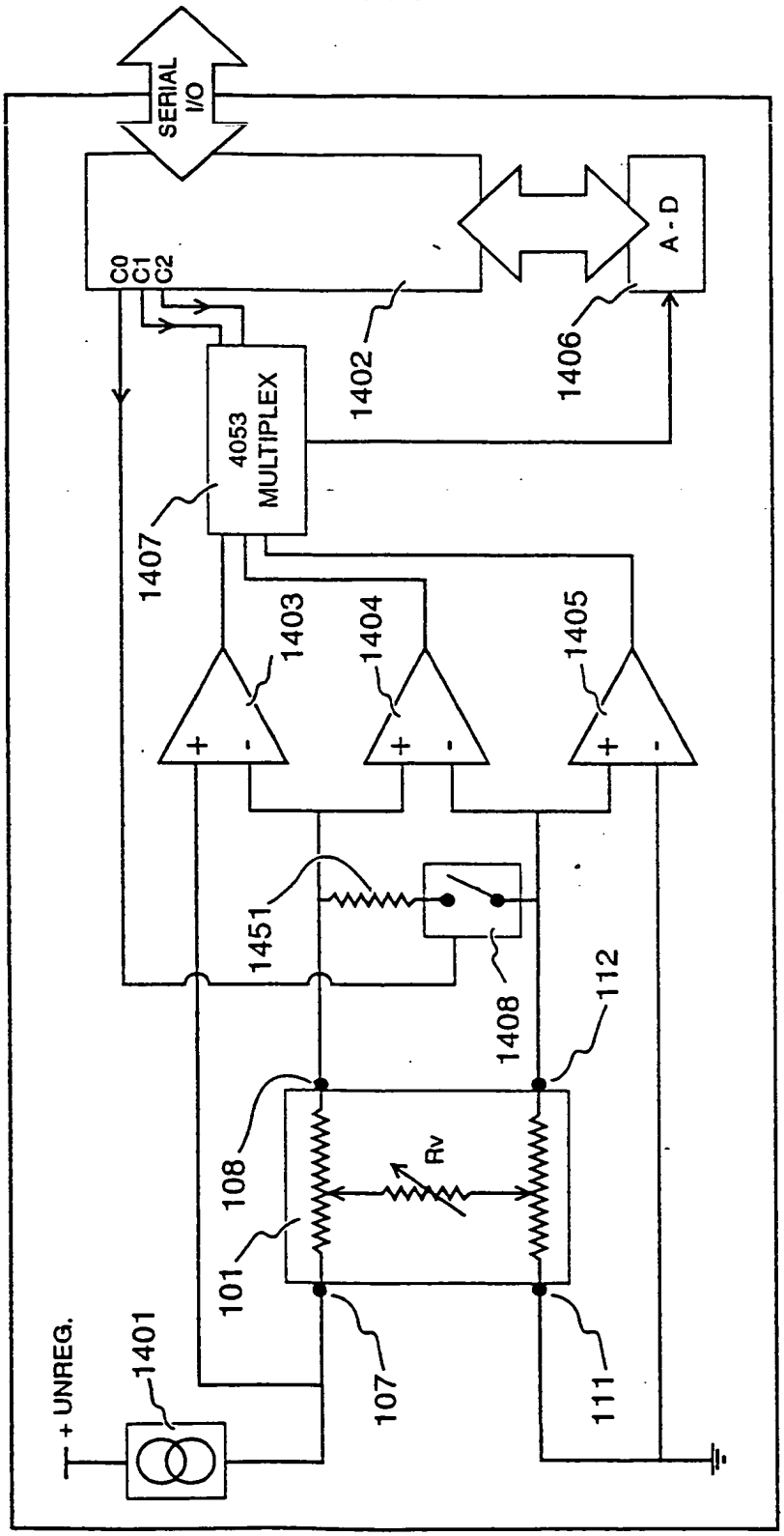

SERIAL I/O
A - D
C0
C1
C2
1402
1406
4053 MULTIPLEX
1407
1403
1404
1405
+
-
1451
1408
112
108
Rv
101
107
111
+ UNREG.
1401

Figure 14